This paper has been presented last September 2002 at the ATM Workshop in Capri. We are proposing to present a revised version of it taking into account the feedback received so far at the Budapest R&D Seminar.

# Absolute versus Relative Navigation: Theoretical Considerations from an ATM Perspective

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*Over the past decades, concepts aiming to improve Air Traffic Management performance have gained significant momentum going from "3D" to "4D" navigation. Procedural Air Traffic Control is historically based upon a knowledge of estimated absolute position over-flight times to provide separation, whilst current radar control service relies directly on a relative representation of the air situation. The proposed evolution to 4D navigation uses absolute representation whereas recent work on Airborne Separation Assistance Systems reinforces the idea of relative navigation. This paper discusses pros and cons of absolute and relative navigation in terms of overall system robustness, in particular system control loops, as well as in terms of potential impact for the human actors, the pilots and controllers. To illustrate the different processes, the information flow between them, the various planning actions and the associated time horizons, the notion of planning layers is introduced and the impact of 4D and 3D navigation on these layers is discussed.*

## Introduction

Over the past decades, from Eurocontrol PHARE to the latest Boeing initiative, concepts aiming to improve Air Traffic Management (ATM) performance have gained significant momentum based on expectations of enhanced time navigation capabilities, going from "3D" to "4D" navigation. Whereas historically, procedural control is based upon a knowledge of estimated absolute over-flight times to provide separation, current radar control service relies directly on a relative representation of the air situation. Whilst the proposed evolution to 4D navigation would switch back to an initial absolute representation, recent work on the evolution of visual clearances, known under the generic term ASAS (Airborne Separation Assistance Systems), reinforces the idea of relative navigation. This paper discusses pros and cons of absolute and relative navigation in terms of overall system robustness, in particular system control loops, as well as in terms of potential impact for the human actors, the pilots and controllers. To better illustrate the different processes, the information flow between them, the various planning actions and the associated time horizons, the notion of planning layers is introduced. This kind of abstraction of the ATM process has been described as early as 1968 by Villiers [1] and has been used since then.

In the next section, the paper discusses the major project and concept examples for first 4D or absolute and than 3D or relative navigation. Thereafter, the current practices of Air Traffic Control (ATC) are described and mapped to the various planning layers. The last section discusses the position of 4D absolute versus 3D relative navigation with regard to the different layers and outlines a possible approach to "the best of both worlds".

## New trends in ATM

The constant pressure to increase airspace capacity has lead to several initiatives to drive change in the current ATM system. These initiatives can be grouped into two main categories. Historically, a large number of initiatives have tried to benefit from so called 4D aircraft capabilities and the ability to fulfil not only lateral and altitude, but in particular absolute time constraints. The concept is to make the aircraft trajectory the focal point and basic working element of ATC, rather than position and velocity. Developments around this concept are still ongoing but more recently a different trend emerged under the term ASAS, investigating the re-allocation of separation related tasks from the controller to the flight deck, and, in particular by letting aircraft – to some extent – manage by themselves their (relative) spacing.

### *"4D tubes in space"*

In the late 80's, the Group for Aeronautical Research and Technology in Europe (GARTEUR) formed an Action Group on the Integration of Flight Management Systems (FMS) and ATM Systems and published a final report in February 1990 [2]. This report introduced the notion of 4D or time-based navigation principles and proposed an ATM system based on air-ground negotiation to define 4D trajectories. This has become known as the "4D tubes in space" concept.

The former Bundesanstalt für Flugsicherung (the German Air Traffic Service provider Deutsche Flugsicherung, DFS) developed a Cooperative Air Traffic Management Concept (CATMAC [3]). Based on the availability of new technologies, in particular FMS and data-link, it assigned a number of relevant ATC tasks to the aircraft, namely (a) precise calculation of the flight profile in 4D, (b) adherence to this profile accepted by the ground system and (c) automatic notification of the ground system when deviations from this profile exceeded agreed limits.

The GARTEUR concept was taken up by PHARE [4], the first common Programme for Harmonised ATM Research in Europe, which brought together the major European ATM Research Establishments (of France, Germany, the Netherlands and the United Kingdom lead by Eurocontrol) with the aim to develop what became known as the PHARE concept.

This concept was based on 4D FMS trajectory predictions, negotiation of trajectories with the ground (and, if necessary, re-negotiation during flight) and guidance and control of the aircraft along these trajectories. The programme ran over ten years, from 1989 to 1999, and included simulations and flight trials with experimental aircraft. In particular, a 4D Experimental FMS was developed for prediction, guidance and control of 4D trajectories, taking into account multiple lateral, altitude and (a novelty) multiple time constraints.

Towards the end of the programme, three demonstrations (human-in-the-loop simulations including flight trials, known as PD1, 2 and 3) showed that 4D guidance along a pre-defined trajectory is technically feasible. However, the impact of such a concept on the roles of pilot and controller as well as the influence of weather on the system was neither properly addressed nor fully understood. Indeed, tactical control was impaired as 4D meant abandoning speed control techniques and reducing the tactical control function to “passive” traffic monitoring. Estimates over reporting points (in absolute time) were available in the FMS but not to the executive controller and, if provided to the ground, would have required the development of different types of graphical representations (such as the timelines of a "railway-chart").

The third demonstration, PD3, added the reduction of complexity through trajectory control at the new multi-sector planning level which corresponded to an introduction of tactical or dynamic flow management. But again, experimental data emphasised the sensitivity of the overall 4D process with regard to uncertainty, especially for departure times. Workload and procedural issues were, equally, not properly addressed in this experiment.

Whilst PHARE remained very much in a research environment, the concept made its way to industry, which is currently running the Aircraft in the Future ATM System programme (AFAS [5]), sponsored by the European Commission. Under the lead of one European aircraft manufacturer and with participation of the avionics industry (plus many research establishments), AFAS investigates basically the same concepts as PHARE, i.e. 4D trajectory prediction, negotiation and establishing of a "contract" between air and ground, guidance and control according to this contract and re-negotiation if necessary.

In the United States similar concepts are under development or partially already implemented. The most important programme is known as Center-TRACON Automation System (CTAS) for Air Traffic Control [6]. Within CTAS, tools such as Descent Advisor, User Preferred Routes, Traffic Management Advisor, Direct-To etc have been developed since the late 70’s at NASA Ames under the lead of H. Erzberger, the "father" of 4D studies in the US. Quite recently, Boeing (respectively its new subsidiary Boeing ATM) published a preliminary concept along the lines of 4D trajectory negotiation, guidance and control [7].

### *Back to 3D relative navigation*

Today's conceptual developments at NASA are known as Distributed Air/Ground Traffic Management which show, interestingly, elements of CTAS on one hand, hence 4D-type of navigation, and on the other "relative navigation" elements such as "self-spacing for merging and in-trail separation" [8]. This integration of the two approaches is also visible in the recent publication of the ICAO ATM Concept Panel [9]. It highlights the key role of the 4D trajectory for a flight (which "will never be allowed to have an open-ended vector", i.e. all manoeuvres must result in a trajectory modification and re-negotiation) and introduces at the same time the notion of cooperative separation, i.e. delegation of the role of the separator to the flight deck.

ASAS concept discussions started in ICAO SICASP (today SCRSP) in 1993 (other uses of the Airborne Collision Avoidance System, ACAS) and continue today, including standardisation issues of Automatic Dependent Surveillance Broadcast, ADS-B [10]. A particular instantiation of ASAS in the US, known as the Free Flight concept, is followed by the RTCA Free Flight steering and selection panels [11] and has been largely experimented, including flight trials, under the Safe Flight 21 programme [12]. This programme explored the use of ADS-B in order to provide common, real-time traffic information to both air traffic controllers and flight crew and has developed, demonstrated and tested applications, procedures, and equipment in the Ohio River Valley (in conjunction with the US Cargo Airline Association) and in Alaska via the Capstone initiative.

In Europe, a multitude of programmes are currently working on ASAS related issues. In Eurocontrol this includes the Freer Flight activities, in particular the Co-Space project focussing on limited delegation [13]. The European Commission sponsors the Mediterranean Free Flight, MFF [14], and the More Autonomous Aircraft in the Future ATM System, MA-AFAS [15], programmes under the lead of ENAV and BAe Systems respectively. MA-AFAS was set-up as counterpart to AFAS with focus on ASAS elements, MFF investigates Free Flight issues in so-called free flight airspace, including limited delegations and autonomous operations, and examines transition issues between this type of airspace and managed airspace.

A series of programmes around ADS-B, i.e. the North-European ADS-B Network and applications Projects, NEAN and NEAP, as well as the NEAN Update Programmes NUP and NUP2 [16], all sponsored by the European Commission, have been set-up to test and validate (with a remarkable participation of airlines such as DLH, SAS and Finnair) the enabling technologies for ASAS. It is worth mentioning that a planned South European ADS-B Programme, sponsored by the European Commission (as another follow-up of NEAN), plans to equip some 50 to 100 aircraft with ADS-B technology.

Under the auspices of Cooperative Actions of R&D in Eurocontrol (CARE), a CARE/ASAS action [17] has been set-up to assure a maximum of information exchange and harmonised development of the principles of ASAS within all European projects under this theme. A European Commission Thematic Network with complementary objectives is planned to start in late 2002.

Important steps to a harmonised development of ASAS applications in Europe and the United States have been taken by the FAA/Eurocontrol R&D Committee under its Action Plan 1. It defines through the Principles of Operations of ASAS (PO ASAS, [18]) the essential elements to advance research in this area in a cooperative manner, taking both US and European perspectives for global applicability into account. In addition, a first definition of those ASAS applications which can be implemented early, has been drafted under the CARE/ASAS action as a Proposal for a First Package of Ground / Airborne Surveillance Applications [19] to the European Commission – Eurocontrol Joint Coordination Board on ADS-B applications.

### *Duality*

A long but in no way exhaustive list of programmes and projects has been enumerated. Nearly all of them can be grouped either under the 4D or absolute, or the 3D or relative type of navigation. However, both on concept as well as on project level there are mixtures of the two approaches or ambiguities such as the ICAO ATM CP concept, the US DAG-TM programme or the European AFAS versus MA-AFAS projects. As an attempt to figure out the key elements let's go back to the basics of ATC.

## Current practices

### *Procedural control*

As described in the ICAO PANS-ATM document, non radar ATC services, also known as procedural control, rely on reports by flight crews over-flying defined reporting positions and providing of their estimates for the next reporting point(s). Therefore, the basic elements handled by controllers are lists of reporting points and associated altitude and times, hence "4D" objects, absolute in terms of position, altitude and time. Different tools such as strip displays (En-route Control Centres), plotting charts (Oceanic) or railway-like charts (former Soviet block) are used by controllers for flight following. These tools provide a geographical arrangement of route structures and reporting points permitting control, based on level, time, distance (DME), angle (VOR radials), geographical or a mixture (as defined in ICAO PANS-ATM). The methodology involves pilot estimates for past, current and next reporting points (provided when passing over a reporting point). A calculation is made to ensure the required separation criteria still hold on receipt of such a report and if necessary a new separation is calculated and applied.

Visual crossing under certain conditions may be used to expedite a separation.

In general, it should be noted that in the construction of the separation minima, the separation (distance or time) is provided between the estimates at the reporting way-points rather than between the actual current positions which are not known. Controllers work with information or predictions reported in a partly non-correlated manner at discrete time intervals which may span several minutes for each individual aircraft. One of their first tasks is to map these pieces of information on the same time reference to be able to analyse the separation situation. Because of the slow situational update, controllers are forced to work at a time horizon of several minutes.

### *Radar control*

The use of radar provides the controller with a time correlated geographical representation of the traffic situation, continuously updated at regular intervals in the order of a few seconds. Therefore, the actual relative spacing of the aircraft can be directly "read" on the radar screen. As a result, controllers are able to work with smaller lead times and are more reactive. However, except for speed vectors with adjustable length, controllers usually have no graphical representation of the future situation on the radar display apart from textual messages or associated paper planning strips. New ground tools like Medium Term Conflict Detection (MTCD [20]), the En Route Assistant Tool (ERATO [21]) or the User Request Evaluation Tool (URET [22]) attempt to expand controllers time horizon through a time based graphical representation. Arrival management tools aim at optimising the aircraft arrival sequence: the most appropriate time to over-fly the reference point is precisely computed for each aircraft. This is then usually converted into a time delay or gain advisory for the controller, hence converting an absolute time reference value in the future to advisories for actions in the short term.

### *Procedural vs. radar control*

The controller works in procedural control in a 4D environment (position with absolute time), while for radar control, it is a 3D relative environment – the time dimension is replaced by speed and relative spacing. It should be noted that the same applies when the flight deck has to perform similar tasks. In non-radar, non-controlled airspace, the Traffic Information Broadcast by Aircraft (TIBA, [23]) is used by flight crews to exchange their current position and estimates between themselves so as to guarantee the safety of their flights – essentially the same information as used by controllers for procedural control. In a radar environment, when performing visual separation (through a VMC clearance), the flight crew relies on pure relative position information (with no explicit time reference), provided to her by the controller at the issuance of the clearance and by her own visual scan during the course of the manoeuvre. This emphases that the type of information available or exchanged – 4D vs. 3D or absolute vs. relative – determines the way the ATC task is performed (rather than the actor) and suggests the need for a systemic approach to understand how new concepts like 4D or ASAS could best enhance ATM operations.

### *Layers and loops*

The ATC system can be modelled as a set of planning levels or layers with sufficiently different time horizons to ensure de-coupling. For layers where feed-back control is present, the notion of control loop or feed-back loop is used in this paper. This is hardly new as quite a few models, which look under different perspectives on the ATM processes, can be found in literature. From a ground perspective, Villiers laid the foundation of such an approach through the notion of layered planning [1]. He introduced a flow management layer to control the sector load, a "procedural control layer" which "filters" the traffic in the most optimal way for the radar controller, the "radar control layer" to resolve residual separation problems and, finally, the "accident layer" which should show, due to the work of the three other layers, the smallest probability possible for an accident (the time for ACAS or the ground-based Short Term Conflict Alert, STCA, being still some years ahead). Under PHARE, PD3 introduced a multi-sector planning layer between flow control and planning, to further reduce traffic complexity.

From the air side, the aircraft and its systems are at the core of the model. The nesting of flight controls, guidance and navigation are classical both for control theory analysis and design (e.g. in [24]), as well as for the understanding of human interactions (e.g. in [25]). Airbus proposed the addition of another layer (a feed-back loop) on top of the classical loops to include ATM with the attempt to coarsely map ATC tasks to the existing loops [26]. Boeing went a step further into refining this approach and providing a synthesis between the ground and the aircraft view [27].

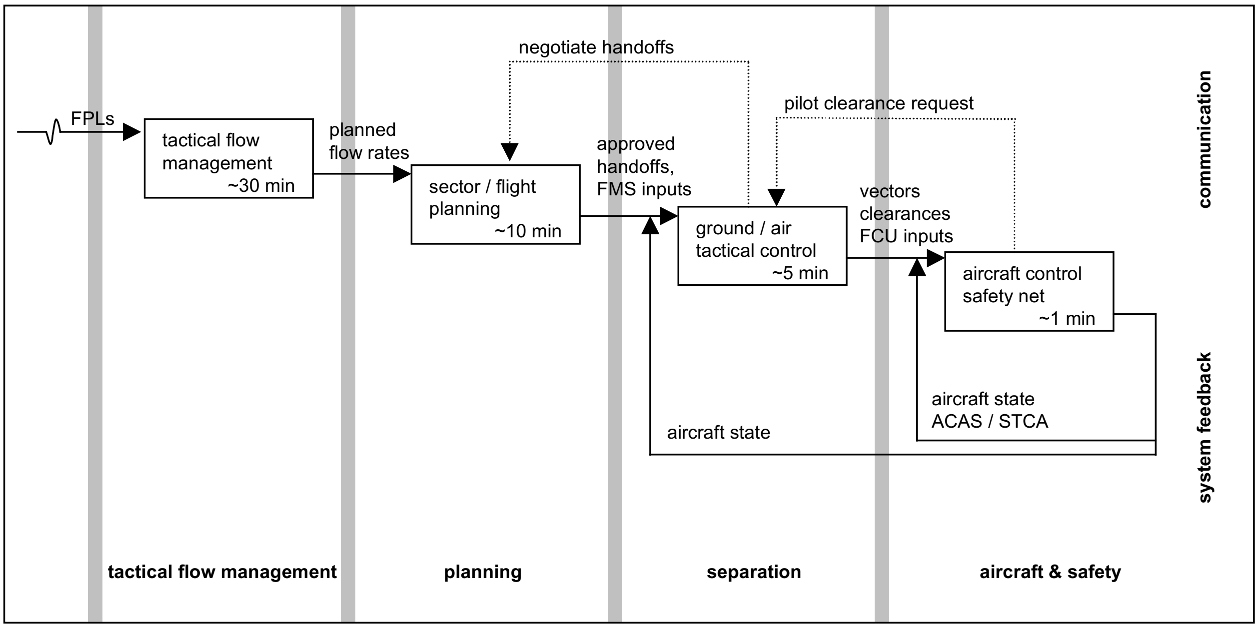

***Figure 1 – The different ATM system layers.***

Largely based on this last model, let us consider a series of layers (see Figure 1 above), starting with the innermost layer, with its associated control loop, at a time horizon of about one minute. This encompasses aircraft control as well as collision avoidance both on air and ground through ACAS and STCA respectively. The next layer above, the tactical control or conformance monitoring layer (to which the separation loop is associated), has a time horizon in the order of 5 minutes and aims at providing separation and flight path guidance (typically target or commanded flight control unit values in terms of heading, speed or altitude). The next layer above can be referred to as the sector flight planning layer with a time horizon in the order of 10 minutes or more, where, considering the aircraft trajectory, some basic de-conflicting is performed. The following layers considered here are for the time being exclusively ground focussed. Real-time flow management, the next layer with a time horizon in the order of 30 minutes, is currently limited to predicting sector loads or traffic complexity with no mechanisms for a feedback or closed control loop through, for example, traffic re-routing (although FAA Traffic Management Units do re-route traffic flows according to weather or sector load constraints). For the time being, the only possible means of action is de-grouping and arming additional sectors as necessary. Further layers, typically all variants of strategic flow management, will be omitted in this paper.

Under procedural control as described above, tactical and planning layers are collapsed together into one planning layer. Update rate, latency and possibly accuracy of the position reports and estimates would not allow for a proper functioning at a time horizon in the order of five minutes as required for the separation loop. On the contrary, in the case of radar control, the emphasis is on the tactical layer with the executive (or radar) controller performing most of the tasks. The planning controller is left with only ancillary tasks, handled within the planning loop. The actions taken by the executive controller (heading, climb/descend and/or speed instructions) in the separation loop introduce "variability" in the data that limits its use by the planning controller. An instruction by the executive controller to solve a problem in his own sector may render the quasi simultaneous work of a downstream controller useless or counterproductive. In other words, there is little value for a planning controller to work on a plan, i.e. a trajectory, if the probability of change of this plan is too high. The "variability" issue is further compounded when the tactical actions lead to "open ended" vectors and thus prevent the trajectory to be updated from current position to destination. As a result, much of the planning task is exit condition based and flight plan update.

The introduction of controller tools such as MTCD might be interpreted as an attempt to offload the executive controller by shifting tasks to the planning controller, possibly taking into account the sensitivity to the data variability. For both planning and executive controller, the fundamental issue at hand is the coupling between the two loops in question: if the time horizon of data and task to be performed are not sufficiently de-coupled, either one controller has to handle both loops or extremely close and costly coordination between the two controllers is required, as provided by the ERATO tool concept of operation [21].

## Discussion

*4D navigation with respect to each of the layers*

4D concepts like those proposed by GARTEUR/PHARE rely on trajectories as the sole object to be used as reference by all layers (except safety net). All information related to each flight is contained in its trajectory and it reinforces the planning loop (see Figure 2-left, below). At the same time, it enables and may activate feedback in the flow management layer, thus associating a feed-back loop to it. However, for separation related tasks, the most relevant information for the controller appears to be relative position, speed and heading. These can be extracted from the trajectories, though at a cost for the controller or her supporting tools. Separation strategies are expressed more naturally in terms of relative position, speed or heading. The implementation of such strategies will again require a conversion with an associated cost to obtain a trajectory. Note that in some cases, the cost can be minimal as the conversions can be made almost transparent to the controller through the use of automation. An example is the Highly Interactive Problem Solver, HIPS [28] which was adapted for the UK Prestwick Oceanic centre.

There is, however, a more fundamental issue attached to the updating of the trajectory: it requires the controller to decide on a complete solution at once - in an almost atomic manner - rather than incrementally build one whilst taking account of the evolution of the situation and so managing variability or uncertainty at the sector level. The variability may cover weather, different or unexpected aircraft behaviour etc., in addition to the impact of her own actions on other aircraft at a later time. This loss of reactivity may have to be compensated by additional separation buffers or margins around the aircraft e.g. a larger tube in space. To partially mitigate the uncertainty on aircraft behaviour and therefore limit the size of the buffers, the trajectories should ideally always come from the aircraft. However, PHARE has shown the need to be able to predict trajectories reliably on the ground so as to provide a reactive trial capability for trajectory update, to cut short the trajectory update negotiation cycles and to manage the sparse air ground data-link bandwidth. This implies to a certain extent "standard" trajectory prediction capabilities for all aircraft and ATC, most likely meaning an updated or new set of avionics, standard airline procedures, … or in reverse and as stated above, the introduction of additional buffers. Furthermore and in terms of workload, the elaboration of a complete solution will either be done in "one shot" - with an implied loss of flexibility in the task and increase in workload management due to larger un-interruptible trajectory "chunks" which will have to be managed - or by inducing a delay (or requiring increased anticipation) to start the implementation of the separation strategy. In short, full 4D with tubes in space for aircraft separation enables tactical flow management, empowers the flight planning function at the cost of a loss of tactical level reactivity and increased workload management for the executive controller.

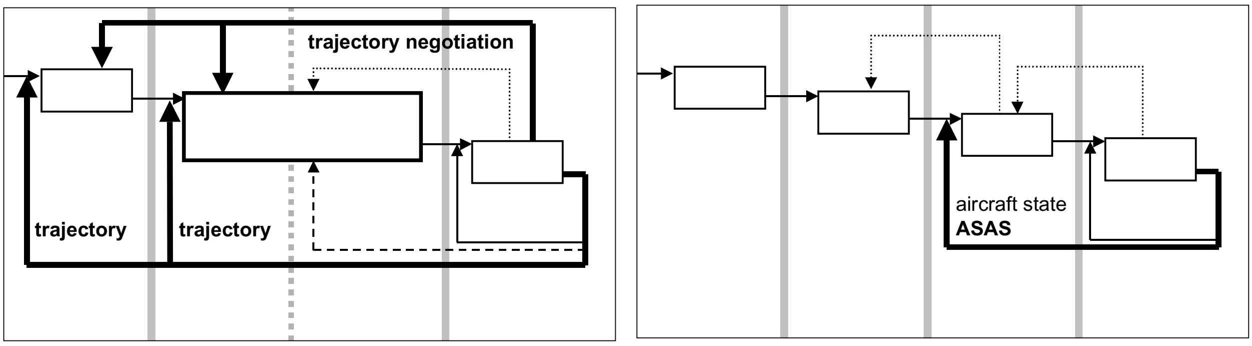

***Figure 2 – 4D navigation (left) and 3D navigation / ASAS (right).***

*ASAS with respect to each of the layers*

The impact of ASAS in the ATM layered model is focussed on the separation loop (see Figure 2-right, above). There is clearly no influence neither on the tactical flow management nor, probably, on the planning layer. Sharing of key separation loop information – position and speed – with other actors is an essential enabler to improve safety and efficiency. The ASAS investigations are based on the expectation that the use of ASAS applications will permit off-loading of tasks performed by the executive controller. In the context of ASAS, these tasks are assigned to the flight deck, but they could possibly be automated or allocated to (an)other ground controller(s). Villiers noted [1] that in procedural control the crossing of designated pairs of aircraft for example could be assigned to specific radar controllers. The planing controller would retain the overall sector view , assigning specific problems to radar controllers on a case by case basis. An analogy, with some caution however due to the responsibility issue, can also be made with visual separation clearances during which a pilot, if he has a traffic in sight, is cleared to provide his own separation.

Initial results from the various projects referenced earlier seem to confirm the feasibility of the ASAS applications. More specifically, they tend to show that a reduction of the executive controller's task load can be achieved (cf. Co-Space experiments [13]). In conjunction with this reduction, the data suggests that it provides greater anticipation for both the controller and the flight crew – giving them longer planning horizons – and thus reducing the number of time critical tasks performed at both sides. The shift in the time-horizon for the controllers may not only be linked to the increased availability but also to the handling of higher level objects: pairs or even clusters of aircraft rather than a single aircraft pair. The shift in the time-horizon for the flight deck is, however, more clearly linked to the use of goal-oriented instructions. The boundaries of the separation loop, e.g. in terms of interactions with the planning and the safety loop, remain unchanged. However, the bandwidth of the separation loop is now split between the two actors: the controller focuses on the low frequency part of it while pilot actions are introduced to cover part of the high frequency side. Using an analogy with classical Bode diagram (frequency vs. magnitude), a possible notional representation can be found on Figure 3 below. At this stage, because typically redundant monitoring by air and ground might be expected, the question remains whether separation is still only one wide band loop or whether it is split into separate air (high frequency) and ground (low frequency) narrow-band loops. In short, the use of ASAS, by reallocating tasks between air and ground within the separation loop and without impacting the other layers seems to increase the availability of the executive controller, which in the current system is one of the limiting factors.

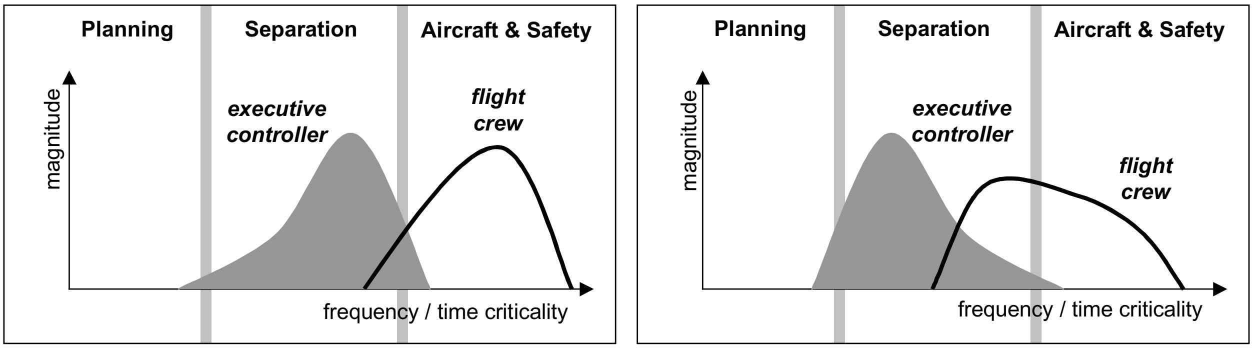

***Figure 3 – Bode diagrams for current situation (left) and 3D navigation / ASAS (right).***

*Some common issues*

Full 4D for separation as well as certain categories of ASAS applications, i.e. the ASAS Separation and Self Separation categories from the ASAS Principles of Operations [18], but notably not the ASAS Spacing category, will require the definition of new separation minima. For 4D, it may mean revisiting procedural like separation minima while for ASAS it means the outright definition of airborne separation minima. The experience and the relative lack of progress over the last decades to reduce separation minima in Oceanic procedural control through the use of ADS highlights the difficulty of such a task. In the same vein, ASAS separation applications (but again not ASAS spacing) raise the question of which human actor is responsible for the provision and monitoring of the separation. The 4D concepts may even push these issues to a new frontier due to the heavy reliance on technology. Since trajectories are the basis for separation, the FMS - today not always fully understood and mastered by its end users - may become a critical element.

No such concept is likely to be implemented in one single step. Segregated airspace may potentially be used to obtain "locally" full traffic equipage conditions and overcome the mixed operations difficulties. Indeed, mixed operations seem to be almost totally impractical for a 4D separation concept while, despite not being ideal for ASAS spacing or separation, it seems to be more acceptable for the latter.

*The best of both worlds*

The main contribution of the use of 4D trajectories appears to be enabling tactical flow management and reinforcing the flight planning function. However, when the use of the trajectories is pushed to its full extent to include separation, the executive controller tasks may be negatively impacted (loss of flexibility, increased complexity). Consequently, in an alternative approach it may be wise to limit the use of trajectories to the planning and the tactical flow management loop and not force them into the separation loop. The main benefits of enabling tactical flow management and empowering planning could still be obtained. The negative impact on the separation loop would disappear, along with the requirement for new separation minima, responsibilities and to a certain extent, mixed equipage.

As the main goal of such approach is flow management and traffic complexity reduction rather than separation provision, it means moving to a more "fuzzy" definition of trajectories with, in particular, the accuracy of time estimates in an order of a minute rather than seconds. Any tactical change would normally time-wise be included in these fuzzier bounds. This is also going away from the strict formal, negotiation-based contractual framework to a more cooperative process with the aim of sharing information among actors. It could consist in making aircraft intent (the FMS trajectory) available to all actors but also, for example, to communicate planned arrival times or slots (and possibly delays) to all upstream sectors and to the aircraft.

By restricting the ASAS part initially to the spacing category as defined in PO ASAS [18], the separation minima issue and responsibility issues could be, at least temporarily, bypassed. Since the ASAS applications is expected to allow for an increased availability of the executive controller without interfering with the other layers, it could be combined with the limited 4D approach described above. The two approaches are not only complementary but seem to be applicable to the most appropriate loops. This is, in essence, almost identical to the "méthode des filtres" proposed by Villiers in his 1968 paper [1].

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